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Joseph W. Haus and H. Sami Sozuer

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Rensselaer Polytechnic Institute
Troy, NY 12180-3590

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13. ABSTRACT *(Maximum 200 words)*

The Grant partially funded an examination of photonic band structures. There were 2 invited talks and 5 publications. We report a new geometry based on stacking layers of dielectric rods; the dispersion curves reveal a large direct band gap. A collaborative experiment-theory effort was developed to characterize new two-dimensional structures with a band gap in the infrared. The lattice constant is three orders of magnitude smaller than all previous reports. Finally, a novel real-space numerical method was applied to one-dimensional structures; the technique can be extended to higher dimensions and it is useful for finite-sized systems and pulse propagation.

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Photonic Band Structures for Optoelectronics

Final Report

by

Joseph W. Haus and H. Sami Sozuer

January 16, 1995

U.S. Army Research Office

Grant Number: DAAH04-93-G-0416

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1 Introduction

Recently periodic dielectric structures, called photonic band structures, with periodicities in three-dimensions have been proposed as a mechanism for eliminating propagating electromagnetic waves over a band of frequencies [1, 2]. By analogy with the band gap in electronic solids, in the dielectric case it was called a photonic band gap. Exercising control over electromagnetic modes implies that the interaction of radiation with matter can be controllably altered. This possibility has motivated a number of researchers [3, 4, 5, 6, 7, 8]; for instance, the spontaneous emission from atoms can be enhanced or suppressed according to whether the density of electromagnetic modes at the atomic transition frequency is larger or smaller than their density in an infinite vacuum.

All previous experimental results on photonic band structures have been restricted to the microwave regime, where the lattice constant can be machined on the order of millimeters [9, 10, 11, 12, 13, 14, 15]. Microwave experiments have determined the transmission characteristics of the photonic band structures. Because the lattice constant is on the order of a wavelength, it has proved difficult to fabricate three and even two-dimensional structures with photonic band gaps in the visible regime.

During the period of this Grant, we were able to report to important new results: 1. new lattice structures with photonic band gaps that can be fabricated in the submicron regime. and 2. the first experimental near-infrared transmittance spectra regime through a two-dimensional structure.

2 Statement of the Problem Studied

The objective of our research was the development of photonic band gap structures with applications to optoelectronics. The research effort was divided into separate projects, each of which was successfully completed.

2.1 Ideal Conductors

To model ideal conductors, we considered only the quasistatic limit. In this regime, an ideal conductor, and to some extent, a superconductor can be modeled by considering its dielectric and diamagnetic properties. The classic textbook example of a point charge near a semi-infinite dielectric medium would make the case. The electric fields in the two regions are found by using the image charge method. For $\epsilon \to \infty$ the dielectric behaves like a conductor as far as the electric field and the polarization surface charge density is concerned. If one further assumes that the charge is moving slowly, then one can assume that its image is moving with it. With this assumption, one arrives at our model for the ideal conductor, namely $\epsilon \to \infty$, $\mu \to 0$ such that $\epsilon\mu = 1$.

Using this model, and letting (ϵ, μ) take the values (10, 0.1) (100, 0.01) and (1000, 0.001) we calculated the band structure for various structures in the simple cubic lattice, and 2-dimensional simple square structures consisting of metal rods, and the inverse structure consisting of cylindrical voids in an ideal conductor. The latter is important in that certain modes should be the same as the wave guide problem, and indeed they are. We were able to calculate the lowest 3–4 waveguide frequencies to a high degree of accuracy using the plane wave method. This is possible despite the high dielectric and diamagnetic contrasts because the wavefunctions associated with these frequencies are exceptionally well behaved and are confined to the cylinders as one would expect from a waveguide. The 3-dimensional structures pose quite a challenge, however, as far as the numerics are concerned. The field discontinuities at the conductor-vacuum interface are enormous and 4 different numerical approaches were used and qualitatively the spectrum obtained from each seem to approach a common value. The work in this area is still not finished and a brief paper summarizing part of the results will be shortly submitted for publication[22].

2.2 Woodpile Structures

A number of different geometries have been shown to possess bandgaps, including the face-centered cubic lattice [16], the diamond lattice[4], the simple cubic lattice[6] and intersecting rod geometries[17]. However, the structures are difficult to fabricate on the scale of centimeters and scaling them to the submicron regime has not been successful. Instead, a new strategy had to be formulated.

HSS has developed a remarkably simple structure by extending a geometry originally proposed by Pendry [18]. The lattice is constructed by placing parallel rods in a plane; the rods can have a rectangular or circular cross-section. A second layer is placed on top of the first again by using parallel rods, but now rotated with respect to the row underneath. The stacking process is continued to build the lattice to macroscopic dimensions. The number of layers in a unit cell is a design parameter. This class of lattices has been called *woodpile structures*[19]. To demonstrate the success of this approach, Sozuer and Dowling[19] considered several different structures.

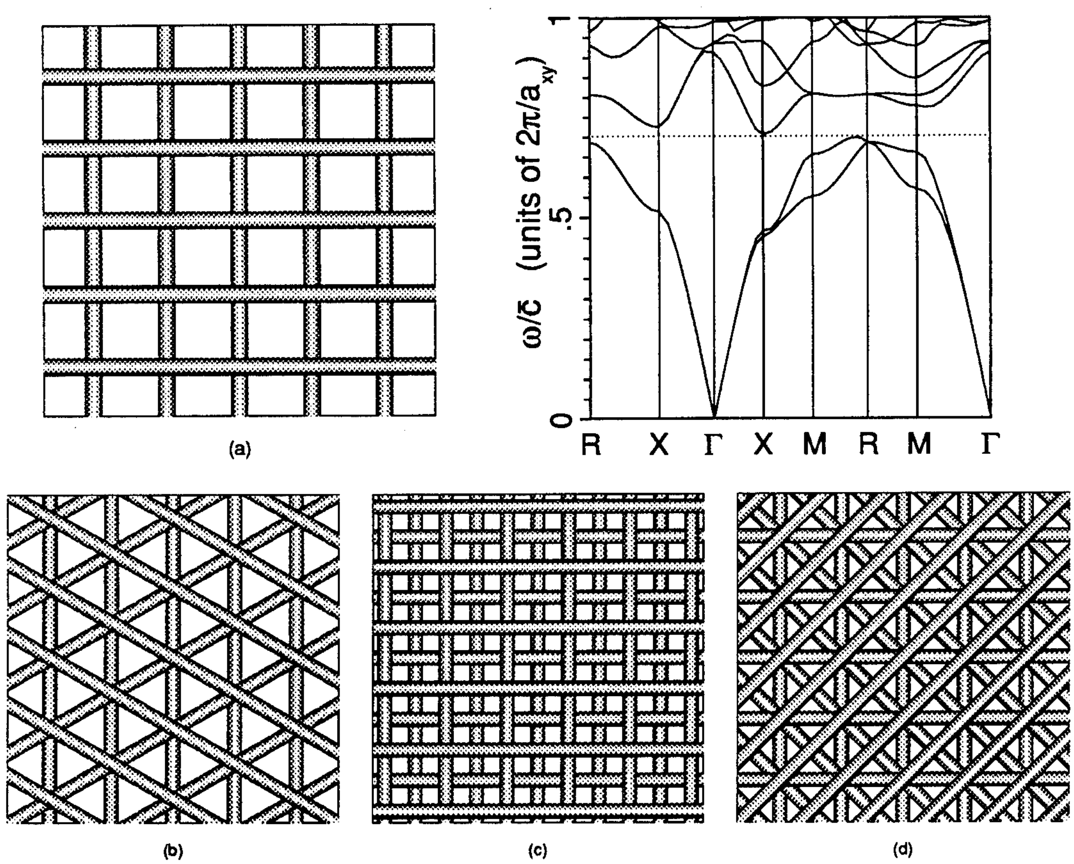

Figure 1: (a) A simple tetragonal rectangular rod structure, and its photonic bands. The rods have a dielectric constant of 16 and occupy 20% of the total volume of the lattice. Other possibilities suggest themselves f one considers modifying the stacking sequence and various other geometrical parameters. The rods are depicted as "round" for ease of viewing, although the most calculations were done for rods of square cross-section. (b) A three-layer simple hexagonal structure. (c) A four-layer body/face-centered structure. (d) Another four-layer structure, but with a simple tetragonal symmetry. Of the four structures shown, the body/face-centered structure exhibited the largest bandgap.

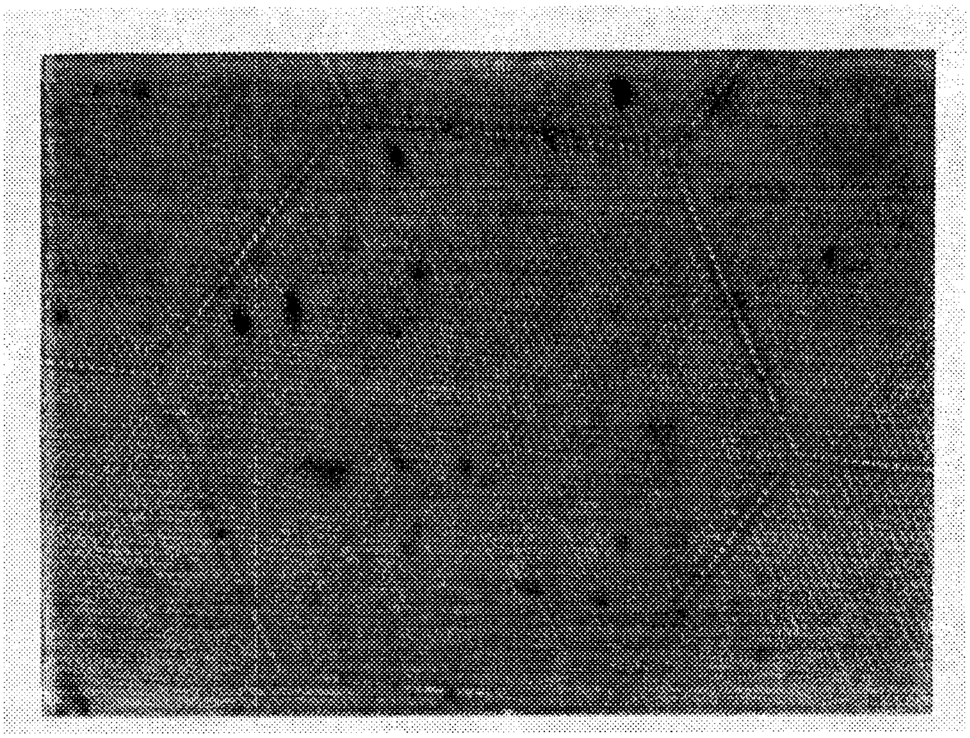

Figure 2: An optical microscope view of channel glass from the top of the sample and magnified by 1000 times. The lattice constant is 1.17 μm and the diameter of the holes is 0.9 μm. The structure is a triangular lattice of air-rods.

2.3 Infrared Bandgap Materials

The group of Prof. K. Inoue in Sapporo Japan had two-dimensional triangular lattice samples supplied by Hamamatsu. The samples are a specially fabricated design using the same technology for producing microchannel plates. A top view of the structure is shown in Figure 2; it is a periodic, parallel array of cylinders with a dielectric constant of 1 (called air-rods hereafter) each having a circular cross-section of diameter 0.90 μm in a background (clad) material of Pb-O glass with a dielectric constant of 2.62. The lattice constant of the periodic lattice is 1.17 μm. The arrays were pulled to a hexagonal shape, whose parallel edges were separated by 64 μm. The sample was fabricated by placing 466 of the hexagonal shaped arrays together to form a quasi-circular bundle of hexagons; the diameter of the bundle is about 1.5 mm. Outside the bundle, the lattice structure is supported by a similar Pb-O glass with a refractive index almost identical with the cladding. The length of the structure is 1.0 mm. The core glass was dissolved by using a HCl acid etch. Direct inspection of the sample by an optical microscope reveals a regular array of holes. Further measurements were made to characterize the sample and insure the uniformity of the air-rods.

The two-dimensional Brillouin zone of the triangular lattice possess two relevant points, besides the Γ-point at the center of the Brillouin zone: the X-point, whose wave vector is $\frac{2\pi}{a}(0, \frac{2}{3}\sqrt{3})$, and the J-point, whose wave vector is $\frac{2\pi}{a}(1, \frac{\sqrt{3}}{3})$; a is the lattice constant. We studied propagation parallel to these directions by polishing two samples whose front and back surfaces of the support glass were flat and perpendicular to the X-point or the J-point.

In Figs. (3) results are shown for the transmittance spectra for the p- and s-polarizations, i.e. E polarized parallel (p-polarization) and E polarized perpendicular (s-polarization) to the rod axis. In the leftmost figure the light is propagated along the Γ- X direction and on the right are the experimental results for propagation along the Γ-J direction.

Consider first the spectra for the X-point direction. An opaque region exists from 3900cm^{-1} to 4600cm^{-1} for the p-polarization and from 3800cm^{-1} to 4300cm^{-1} for the s-polarization. This is the inherent photonic band gap of the structure and is supported by calculations. Beyond 4600cm^{-1} no complete reflections were

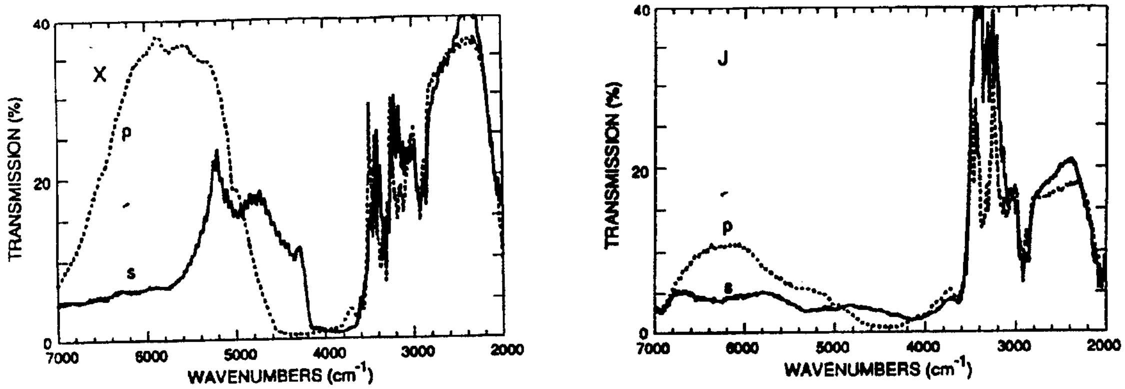

Figure 3: Transmittance spectra for p- and s-polarizations corrected for the absorbance of the intrinsic glass below 3600 cm^{-1} wavenumbers. (left) the absorbance along the Γ-X direction; (right) the absorbance along the Γ-J direction.

observed. For the s-polarization, on the other hand, no opaque region is recognized over the entire observed range.

With the lattice spacing and hole diameter for our sample the filling factor of air-rods is 0.537. A total of 271 plane waves for each polarization was used to calculate the dispersion spectra. The p-polarization has a gap for all direction in the 2D Brillouin zone, even though the dielectric constant is very large. For the s-polarization though, the degeneracy at the J-point persists. We have tried to break the degeneracy by using elliptical shaped holes, but that has not produced the desired results.

2.4 A Novel Numerical Approach

Numerical approaches to photonic band structure calculations are still underdeveloped. New methods are needed to improve the flexibility of the modeling. Plane–wave methods are well suited to studying infinite lattice and dielectric functions that are real. They are hampered by convergence problems though, that can be overcome by using several different methods that hopefully converge to one another in the limit of an infinite number of plane waves.

Pendry and MacKinnon [18] applied a transfer matrix method to the solution to a finite lattice. Advantages of the method are its use on finite lattices, applicability to complex dielectric functions and its ability to describe dispersive media.

Scalora and Crenshaw [20] developed a generalization of the beam propagation algorithm that has been used in nonlinear optics. This method has all the advantages of the method of Pendry and MacKinnon and it can be used for nonlinear media and is useful to describe pulse propagation. We have applied this new method to two different problems: 1. the propagation of a pulse through a photonic bandgap structure and 2. the emission rate of a dipole embedded in a photonic band structure.

The first problem is important because it addresses the nature of the so-called superluminal tunneling times of a pulse[21]. After examining the energy flow through the lattice, we found that the apparent superluminal tunneling is due to a reshaping of the pulse in passage through the lattice. The local momentum and energy density in the structure reveal that the speed of the pulse never exceed the speed of light in vacuum.

In the second problem the power radiated by classical dipole oscillators is studied as a function of frequency. The power radiated peaks at an order of magnitude above the free space radiation rate near the band edge and the spontaneous emission rate was suppressed by three orders of magnitude with respect to free space in the bandgap region.

2.5 Future Research

There are many problems that remain to be solved. We briefly mention some that have are of special interest. First, the band gap can be made much larger if a combination of electric and magnetic material properties are investigated; this has been a concentration of our efforts over the past year and will remain so in the future. The convergence problems become more delicate in this instance and we are sorting out the answers now. Second, the new experimental structures are amenable to investigations with pulse lasers; hence, it is important to bring the new numerical method to bear on these problems to predict the pulse reshaping after reflection from the surface and multiple scattering inside the medium. Also, this would be an excellent opportunity to develop multiple scales perturbation methods to provide new tools for analysis of light propagating through the structures. Third, the structures can be filled with a gas possessing a resonant nonlinearity near the band edge or even in the gap. The propagation of light in the structure and the transmission coefficient would depend on the intensity. This would form an interesting new class of resonantly enhanced nonlinear materials.

3 Summary of the Most Important Results

- We studied the photonic band structure of ideal conductors. The results are encouraging in that certain well-known results can be reproduced using this model which relies on local properties, $\epsilon(\mathbf{r})$ and $\mu(\mathbf{r})$ of the material rather than using boundary conditions at the vacuum-conductor interface.
- HSS, in collaboration with Jon P. Dowling of the U.S. Army Missile Command studied a new photonic band structure geometry based on stacking layers of rods on top of one another. These structures are dubbed *woodpile structures*. By varying the stacking sequence and other geometrical parameters numerous structures with large bandgaps have been designed. The major attraction of these structures is, of course, that they can be "grown" in the stacking direction and are, or should be, much easier to fabricate than previously proposed geometries.
- JWH collaborated with an experimental group in Sapporo, Japan to study the linear optical properties of a two-dimensional triangular lattice with lattice constants of 1.17 μm. This is the first experiment in the infrared wavelength regime. The wavelengths for the band gap are three orders of magnitude smaller than all previous reports.
- Using a real-space numerical method developed by Michael Scalora at the U.S. Army Missile Command, we applied it to pulse propagation and dipole emission rates in one-dimensional photonic band structures. This technique is applicable to pulses and finite-size systems and appears to be very promising.

4 List of Publications

1. J. W. HAUS, *"A Brief Review of Theoretical Results for Photonic Band Structures,"* Journal of Modern Optics **41**, 195-207 (1994).
2. H. S. SOZUER AND J. P. DOWLING *"Photonic Band Calculations for Woodpile Structures,"* Journal of Modern Optics **41**, 231-239 (1994).
3. K. INOUE, M. WADA, K. SAKODA, A. YAMANAKA, M. HAYASHI AND J. W. HAUS, *"Fabrication of Two-dimensional Photonic Band Structures with Near-infrared Band Gap,"* Japanese Journal of Applied Physics **33**, L 1463-L 1465 (1994).
4. M. SCALORA, J. P. DOWLING, A. S. MANKA, C. M. BOWDEN AND J. W. HAUS, *"Pulse Propagation near Highly Reflecting Surfaces: Applications to Photonic Bandgap Structures and the Question of Superluminal Tunneling Times,"* Physical Review A, in review (1994).

5. M. SCALORA, J. P. DOWLING, M. TOCCI, M. J. BLOEMER, C. M. BOWDEN AND J. W. HAUS, *"Dipole Emission Rates in One-dimensional Photonic Band Gap Materials,"* *Zeitschrift für Physik B*, in press (1994).

6. H. S. SOZUER, *"Photonic Band Structure of Ideal Conductors,"* in preparation (1995).

5 Talks

Two invited talks and two contributed talks were presented at conferences.

5.1 Invited Talks

1. J. W. HAUS AND H. S. SOZUER, *"Photonic Band Structures for Optoelectronic Applications,"* Progress in Electromagnetic Research Symposium, Pasadena, CA, July 12-16, 1993.

2. J. W. HAUS AND H. S. SOZUER, *"Photonic Band Structures for Optoelectronics,"* Frontiers in Information Optics, Kyoto, Japan, April 4-8, 1994.

5.2 Contributed Talks

1. K. INOUE, M. WADA, K. SAKODA, A. YAMANAKA AND J. W. HAUS, *"Near IR Transmittance of a 2D Photonic Band Structure,"* Annual Meeting of the Optical Society of America, October 2-7, 1994, paper MI2.

2. M. SCALORA, J. P. DOWLING, A. S. MANKA AND J. W. HAUS, *"Electromagnetic Pulse Propagation Near Highly-reflective Surfaces,"* Annual Meeting of the Optical Society of America, October 2-7, 1994, paper ThAA3.

6 Scientific Personnel Supported

The Grant was used to support H. Sami Sozuer as a postdoctoral research associate during the year. He is presently a postdoctoral research associate at Mississippi State University.

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